Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)* Naval Research Laboratory Washington, D.C. 20375	2a. REPORT SECURITY CLASSIFICATION Unclassified	
	2b. GROUP	
3. REPORT TITLE EFFECT OF SHEET THICKNESS ON THE FRACTURE-RESISTANCE PARAMETER K_c FOR STEELS		
4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)* Final report on one phase of a continuing NRL problem.		
5. AUTHOR(S) *(First name, middle initial, last name)* A. M. Sullivan and J. Stoop		
6. REPORT DATE August 8, 1973	7a. TOTAL NO. OF PAGES 19	7b. NO. OF REFS 13
8a. CONTRACT OR GRANT NO. NRL Problem M01-24 b. PROJECT NO. RR 022-01-46-5431 c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) NRL Report 7601 9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*	
10. DISTRIBUTION STATEMENT Approved for public release; distribution unlimited.		
11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Department of the Navy Office of Naval Research Arlington, VA 22217	

13. ABSTRACT

Definition of fracture resistance for thin-sheet material in terms of the linear-elastic fracture mechanics (LEFM) plane-stress parameter K_c continues to reveal aspects of its geometrical dependency. The effect of sheet thickness on the K_c value of three structural steels representing four yield stress levels has been determined over available thickness ranges of 1/32 to 1/4 in. Within this range, less thickness dependence has been observed than was anticipated.

The facts that both economy and convenience would be served if fracture resistance for all sheet thicknesses could be estimated from a limited number of specimens have given impetus to several models purporting to explain this dependency in terms of the relative contributions of a surface phenomenon, flat fracture, and a volume-sensitive mechanism, shear-lip development. Attempts to fit present data to one of the models disclose inadequacies for which there are no apparent immediate solutions.

DD FORM 1 NOV 65 1473 (PAGE 1)

S/N 0101-807-6801

Security Classification

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Linear-elastic fracture mechanics						
Plane stress						
Thin-sheet steel						
High-strength steel						
Fracture-resistance parameter K_c						

DD FORM 1 NOV 65 1473 (BACK)
(PAGE 2)

Security Classification

CONTENTS

ABSTRACT

Definition of fracture resistance for thin-sheet material in terms of the linear-elastic fracture mechanics (LEFM) plane-stress parameter K_c continues to reveal aspects of its geometrical dependency. The effect of sheet thickness on the K_c value of three structural steels representing four yield stress levels has been determined over available thickness ranges of 1/32 to 1/4 in. Within this range, less thickness dependence has been observed than was anticipated.

The facts that both economy and convenience would be served if fracture resistance for all sheet thicknesses could be estimated from a limited number of specimens have given impetus to several models purporting to explain this dependency in terms of the relative contributions of a surface phenomenon, flat fracture, and a volume-sensitive mechanism, shear-lip development. Attempts to fit present data to one of the models disclose inadequacies for which there are no apparent immediate solutions.

PROBLEM STATUS

Final report on one phase of a continuing NRL problem.

AUTHORIZATION

NRL Problem M01-24
Project RR 022-01-46-5431

Manuscript submitted April 25, 1973.

SYMBOLS

A	Area
$2a, 2a_c$	Crack or notch length in a sheet; the subscript c refers to the critical value.
k_{ff}, k_{SL}	Material constants: the subscript *ff* refers to a flat fracture; SL refers to shear lip.
B	Specimen thickness
B_{SL0}	Critical (constant) shear-lip thickness
CCT	Center-crack tension specimen
COD	Crack-opening displacement
E	Young's modulus
K_c	Fracture-resistance parameter; the subscript c refers to the critical value load
LEFM	Linear-elastic fracture mechanics
P	Load
W	Specimen width
$\mathcal{G}_c; \mathcal{G}_{Ic}$	Strain-energy release rate per unit area; crack extension force; the subscript c refers to the critical value; the subscript I refers to the opening mode of fracture.
σ_G	Gross or nominal stress P/A
σ_{op}	Operating stress
σ_{ys}	Yield stress

EFFECT OF SHEET THICKNESS ON THE FRACTURE-RESISTANCE PARAMETER K_c FOR STEELS

INTRODUCTION

Fracture resistance can be defined as a measure of the ability of a material to withstand the deleterious effects of cracks, flaws, or notches while under stress. Rapid and catastrophic failure may occur at nominally elastic stress levels when such discontinuities are present in materials exhibiting low levels of fracture resistance.

Since all materials and structures will contain cracks or cracklike defects, a key step toward fail-safe design is the incorporation of some measurement of fracture resistance in material specifications. Particularly suitable in this regard are the parameters of linear-elastic fracture mechanics (LEFM) which specify the magnitude of stress or length of crack required to cause catastrophic failure.

For thin-sheet materials (essentially under conditions of plane stress), this parameter, designated as K_c, has been found to be sensitive to geometric variables caused by the physical restrictions of laboratory specimens. The dependencies of K_c on specimen width and crack length-to-width ratio have been extensively studied (1 - 9).

Figure 1 illustrates these dependencies; the surface represents a K_c value of 100 ksi $\sqrt{in.}$ By assuming a yield stress of 60 ksi for this hypothetical alloy, the hatched plane area parallel to the base plane separates the region in which yielding has occurred (above) from that in which yield has not occurred, where valid K_c data may be obtained. It is axiomatic in LEFM that the specimen be under elastic stresses only. However, it is of course recognized that a small enclave of plasticity will be obtained at the crack tip. These recognized dependencies provide correction factors and guides for testing procedures so that valid measurements can be assured. Up to the present, however, no standards have been adopted, though all research is being directed to this desirable end.

The influence of sheet thickness on K_c, although also an important variable, has received less attention than the aforementioned geometric variables. For this reason, an examination of the effect of sheet thickness on the K_c value for steel sheet alloys of differing yield stress has seemed worthwhile. Comparison is possible with analogous studies incorporating sheet specimens of aluminum and titanium alloys.

EXPERIMENTAL PARAMETERS

Material

The fracture resistance of three steel sheet alloys representing four yield-stress levels has been investigated. Mechanical-property data and fracture-resistance values are presented in

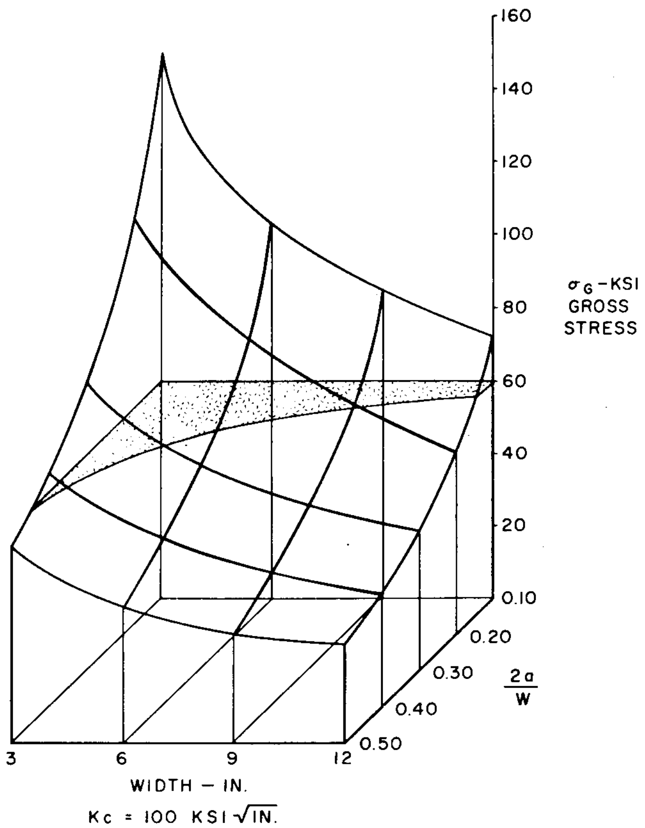


Fig. 1—Effect of width and crack length on instability stress. Surface: K_c = 100 ksi$\sqrt{in.}$; parallel plane: $\sigma = \sigma_{ys} = 60$ ksi.

Table 1; heat treatment is presented in Table 2. All alloys were tested so that the path of fracture was parallel to the rolling direction (TL) since if anisotropy is present this will be the direction less resistant to fracture. It is evident that the level of fracture resistance in the weaker direction should categorize materials unless the direction of operating loads can be absolutely assured.

Test Procedure

The specimen employed is the center-cracked tensile (CCT) sheet illustrated in Fig. 2. Not only is this specimen a natural structural prototype precursor, but the stress analyses are well documented. The width of all specimens was 12 in. (30 cm). Central slits were produced by an electric-discharge method, Elox, to give a 0.063-in. (0.16-cm)-wide slit with slit tip radii typically 0.003-0.006 in. (0.008-0.015 cm), designated "blunt." To assess the effect of tip radius on K_c, companion specimens had slits sharpened by a second Elox operation with a fine electrode. This extended the slit 0.05 in. (0.13 cm) at each end with a slit width of 0.002 in. (0.005 cm) and a tip radius of 0.001 in. (0.0025 cm). Although ideally an extension of the initial slot by fatiguing is desirable to produce a "natural" sharp crack tip, it is unnecessary when some crack growth precedes final instability (10).

To calculate fracture resistance as K_c for this CCT specimen, the appropriate equation (9) is

$$K_c = \sigma_G \sqrt{\pi a_c} f \frac{2a}{W}. \qquad (1)$$

Table 1
Composition and Heat Treatment of Steels

Steel	C	Mn	P	S	Si	Ni	Cr	Mo	V	Co	Ti	Al	Zr	B	Ca	Austenitizing Temperature (°F)	Tempering Temperature (°F)
4130 A*	0.33	0.53	0.29	0.006	0.016	–	0.94	0.20	–	–	0.44	0.15	0.02	0.003	0.06	1575 (1 Hr) WQ¶	700 (30 min) AC§
4130 B*	0.33	0.53	0.29	0.006	0.016	–	0.94	0.20	–	–	0.44	0.15	0.02′	0.003	0.06	1575 WQ¶	500 (30 min)
D6A	0.45-0.50	0.60-0.90	0.015	0.015	0.15-0.30	0.40-0.70	0.90-1.20	0.90-1.10	0.08-0.15	–	–	–	–	–	–	1630 (30 min) AC§	Double Temper: 600 (2 hr) AC§; 600 (2 hr) AC§
RSM 250†	0.03	0.05	0.003	0.006	0.09	17.9	–	4.86	–	7.41	0.44	0.15	0.02	0.003	0.06		900 (3 hr) AC§

*NRL values
†Certified analysis
¶WQ = water quench spray
§AC = air cooled

Table 2
Mechanical and Fracture-Resistance Properties of Four Steels

Steel	Sheet Thickness (in.)	σ_{ys}* (ksi) (0.2% offset)	σ_{ts}* (ksi)	Elongation (%)	Reduction in Area	Blunt		Sharp	
						$\frac{2a}{W}$	K_c† (ksi$\sqrt{in.}$)	$\frac{2a}{W}$	K_c† (ksi$\sqrt{in.}$)
4130 A (700°F)	0.030	167.8	183.4	–	7.1	0.30	136	0.33	151
						–	–	0.57	146
	0.050	171.6	197.6	3.5	7.5	0.26	133	0.38	172
						0.48	146	0.56	174
	0.063	169.5	193	3.8	11.2	0.23	156	0.32	172
						0.32	163	0.54	191
						0.40	156	–	–
						0.42‡	161	–	–
						0.31‡	162	–	–
	0.087	183.4	205.2	3.0	6.5	0.22	127	0.27	124
						0.38	124	0.51	144
	0.125	176.4	197.9	4.5	16.5	0.26	151	0.30	148
						0.40	146	0.48	158
	0.25	173.7	195.3	7.5	36.8	–	–	–	–
4130 B (500°F)	0.032	185.2	221.4	2.5	7.1	–	–	0.42	154
						–	–	0.56	161
	0.050	184.6	219.8	3.0	10.7	0.22	130	0.26	146
						0.60	168	0.55	158
	0.063	178.4	226	5.2	27.8	0.20	135	0.22	129
						0.29	128	–	–
						0.38	141	0.51	146
						0.47	159	–	–
	0.087	200.3	233.2	3.5	20.1	0.26	124	0.33	123
						0.42	120	0.54	127
	0.125	191.2	228.1	6.0	23.2	0.28	158	0.31	155
						0.52	172	0.41	138
	0.25	185.4	221.5		36.9	–	–	0.45	163
						0.33	124	0.35	121
D6A	0.098	228	246.5	4.0	16.2	0.166	72.8	0.18	54.8
						0.33	62.4	0.34	61.6
	0.190	219.7	255.3	5.5	19.3	0.16	69.8	0.18	47.6
						0.33	61.2	0.34	45.1
	0.25	230.0	269.5	7.5	27.8	0.16	87.6	0.18	68.2
						0.33	111.7	0.34	86.1
RSM 250	0.063	243.5	253.6	3.2	21.1	0.20	194	0.22	180
						0.42	213	0.50	207
	0.090	246.4	255.2	5.0	35.4	0.19	204	0.24	204
						0.42	221	0.40	204
	0.140	247.7	255.8	4.7	37.9	0.28	230	0.25	194
						0.40	202	0.42	186

*ksi × 6.895 = MN/m²
†ksi$\sqrt{in.}$ × 1.098 = MN$\sqrt{m}$/m²
‡hole + slit

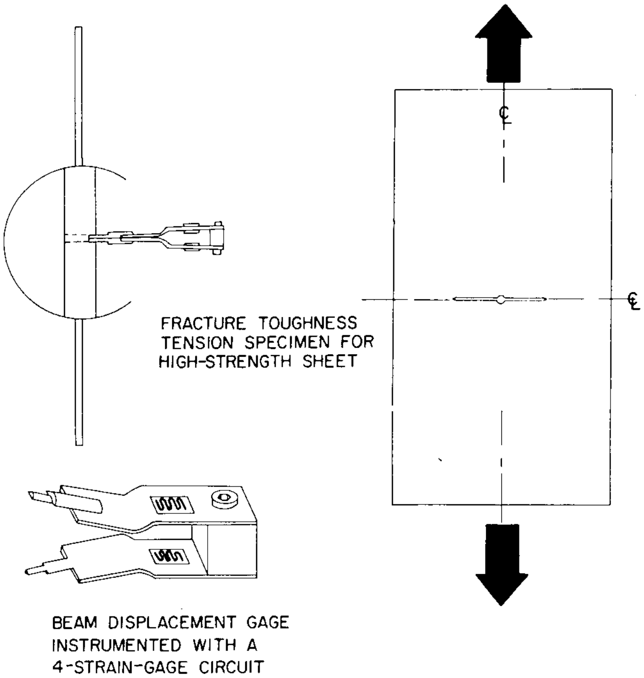


Fig. 2—Center-crack tension (CCT) specimen and displacement gage used to measure center hole opening (COD)

It has been established (11) that for a range of 2a/W values between 0 and 0.6, the following expression is accurate to within 1 percent:

$$f\frac{2a}{W} = 1.77\left[1 - 0.1\left(\frac{2a}{W}\right) + \left(\frac{2a}{W}\right)^2\right]. \tag{2}$$

Since load and crack length are required, when the specimen is loaded in tension, load and central crack-opening displacement (COD) are simultaneously graphed by an XY recorder until failure occurs. Crack-opening displacement is measured by a strain-gage-instrumented probe positioned in a circular hole in the center of the initial slit. This COD measurement is referred to a normalized calibration curve which relates the amount of crack opening to the instantaneous crack length of the specimen. Full details of this procedure have been published (1). This technique delineates the "effective" crack length (actual crack plus plastic zone), and therefore the plastic-zone correction factor is not used in the K_c calculation.

EXPERIMENTAL RESULTS

Definition of Instability

Figure 3 illustrates two types of crack-extension behavior observed. When a sheet specimen containing a notch is loaded in tension, a certain load level must be attained before a crack is initiated at the notch tip: Region I defines this load. Once formed, the crack will grow under a rising load, Region II, until, for brittle alloys at a critical combination of load and crack length, instability and immediate final separation occur. With tougher materials, however, separation does not occur at the end of Region II. Instead the crack growth rate accelerates while the load on the specimen remains constant, Region III. Final separation occurs only after this period of growth at constant load. However, since for practical purposes structural integrity is lost at the

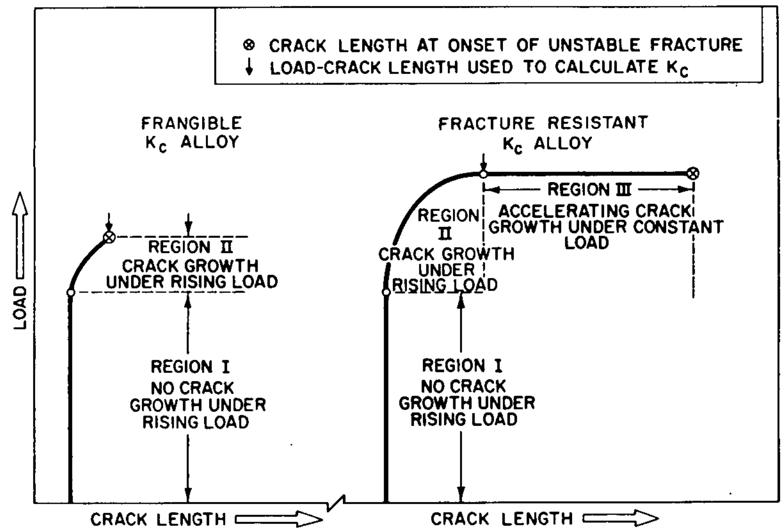


Fig. 3—Comparison of the load and crack-length record of a brittle and a moderately tough alloy

end of Region II behavior, the load and crack length at this point are used to calculate K_c. This type of crack-extension behavior, Region III, was observed with the 4130 steel. The amount of crack growth at constant load tends to decrease with increased sheet thickness.

Effect of Sheet Thickness on K_c

Figure 4 illustrates the anticipated dependency of K on specimen thickness B. At some sheet thickness, specific for each alloy, a maximum value of K_c should be obtained and be accompanied by 100-percent slant fracture. As the thickness increases, lower K_c values are accompanied by increasing amounts of flat fracture to provide the so-called "mixed-mode" appearance. Finally a minimum value K_{Ic} is reached, and the fracture surface is entirely flat.

How closely this anticipated behavior is achieved in real materials, the steels of this investigation, is seen in Figs. 5a-5d. In these figures K_c is plotted against sheet thickness B; an accompanying plot also indicates the amount of slant fracture observed on the fracture surfaces. Although

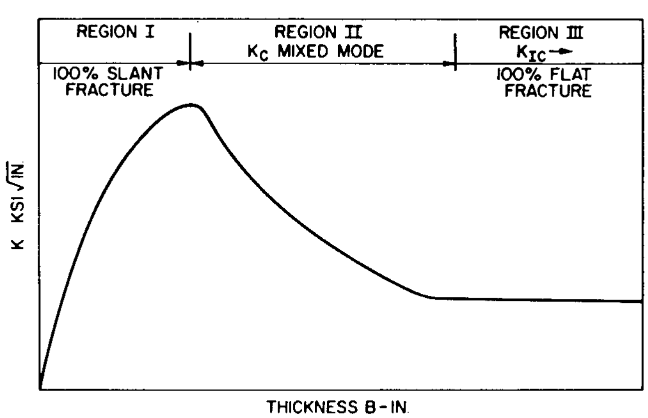
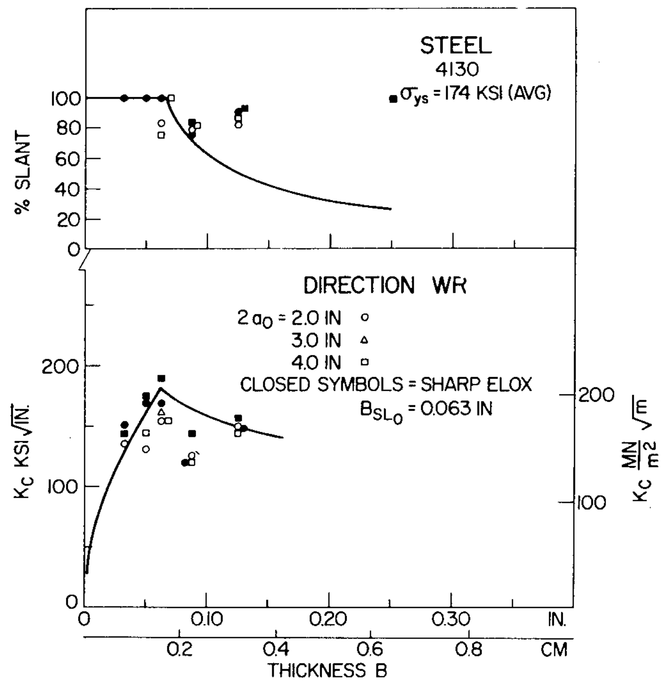
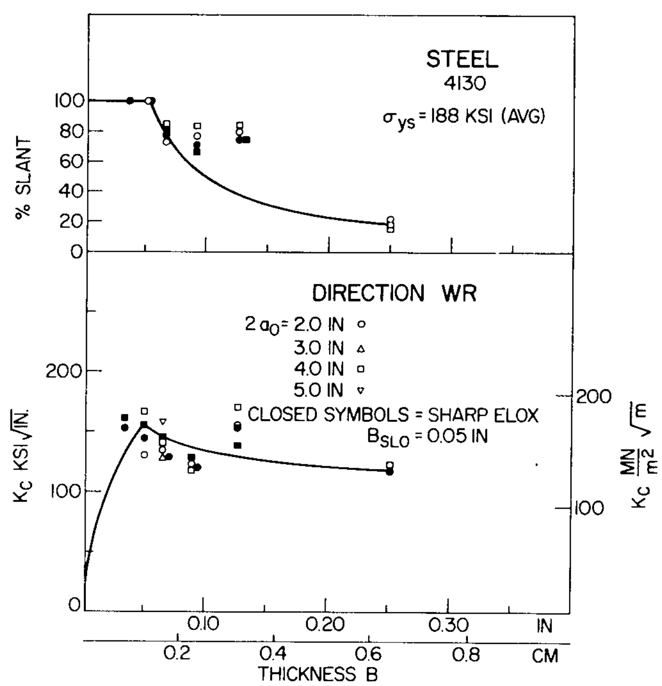


Fig. 4—Postulated influence of the specimen thickness B on the fracture-resistance parameter K_c

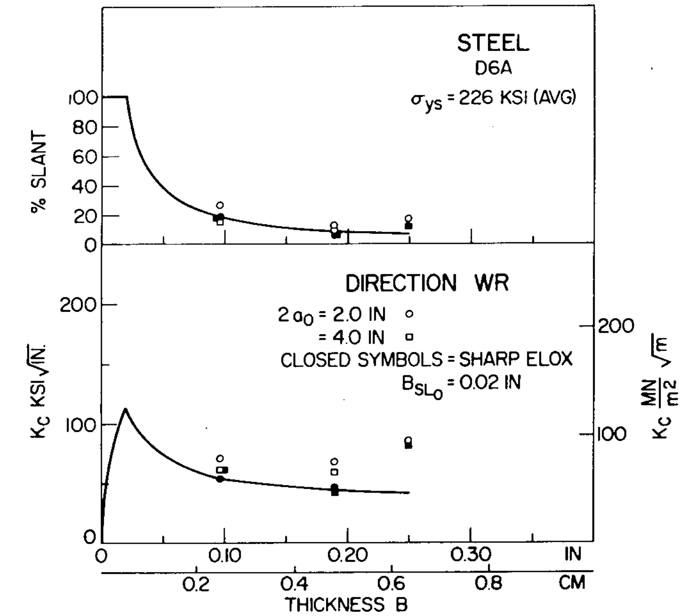


(a) 4130A steel

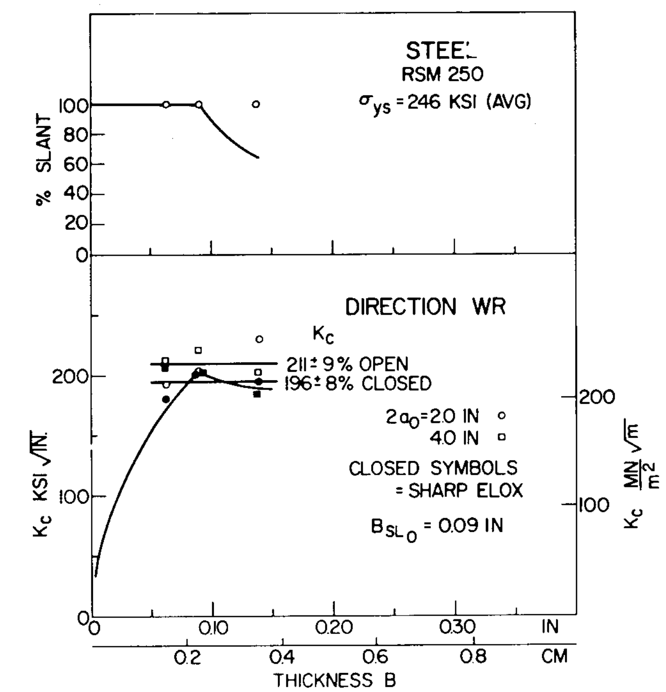


(b) 4130B steel

Fig. 5—Measured K_c values (lower curve) and slant-fracture percent (upper curve) vs specimen thickness B. The curves drawn are calculated from the model of Ref. 12.



(c) D6A steel



(d) RSM 250 steel

Fig. 5 (Continued)—Measured K_c values (lower curve) and slant-fracture percent (upper curve) vs specimen thickness B. The curves drawn are calculated from the model of Ref. 12.

it is perhaps not quite correct to designate the values as K_c since they are generally "mixed-mode" fractures, this nomenclature has become customary. Curves drawn through the two sets of data points were obtained from an analytical model and will be discussed in a later section of this report.

Some dependence of K_c on sheet thickness is observed. Values obtained from test specimens containing "sharp" Elox slit tips are in general the same as those from specimens containing the "blunt" slit tips. Ideally an extension of the initial slit by fatiguing is desirable to produce a "natural" sharp crack tip. When some crack growth precedes final separation, this tip sharpening has been considered unnecessary (10).

APPLICABILITY OF A MODEL FOR THE SHEET-THICKNESS DEPENDENCY ON K_c

Since some variation in fracture resistance with sheet thickness is observed, it would obviously be a convenience if fracture resistance for all sheet thicknesses could be estimated from a limited number of actual measurements. Two quite similar models have been developed purporting to explain the effect of material thickness on the value of K_c (12, 13). Both models define flat fracture as a surface phenomenon and shear-lip formation as a volume-sensitive mechanism. It is further postulated that once the shear lip is fully developed the total lip width no longer increases. This is conceptualized in Fig. 6a. The relevant equations are:

Model I

$$\mathcal{G}_c = \frac{1}{2} k_{SL} B_{SL0} \left(\frac{B}{B_{SL0}}\right), \quad \frac{B}{B_{SL0}} \leq 1; \tag{3}$$

$$\mathcal{G}_c = \frac{1}{2} k_{SL} B_{SL0} \left(\frac{B_{SL0}}{B}\right) + k_{ff}\left(1 - \frac{B_{SL0}}{B}\right), \quad \frac{B}{B_{SL0}} \geq 1. \tag{4}$$

Model II

$$R = \mathcal{G}_c = \frac{1}{2} k_{SL} B_{SL0} \left(\frac{B_{SL0}}{B}\right) + k_{ff}, \tag{5}$$

where $\mathcal{G}_c = K_c^2/E$, B_{SL0} is the critical (constant) shear-lip thickness, B is the sheet thickness, k_{SL} and k_{ff} are material constants (subscripts SL and *ff* refer to shear lip and flat fracture respectively), and $k_{ff} = \mathcal{G}_{Ic}$.

Examination of Eqs. (3)-(5) shows that Models I and II differ only in an evaluation of the contribution of the flat-fracture portion. The application of Model I to the data presented here has been attempted. First, consider the plot of absolute shear-lip width, B_{SL} vs thickness B, for all steels seen in Fig. 6b. Only D6A steel indicates a possibly constancy of shear-lip thickness. Referring back to Figs. 5a-5d however, it is noted that the percent of slant fracture generally decreases with thickness. For this reason, rather arbitrary choices of B_{SL0} were necessitated.

Curves were calculated from this model and are plotted together with the measured data points in Figs. 5a-5d. These curves do not indicate a high degree of correspondence. Nonetheless, albeit crudely, trends are shown which may be more exact with more uniform material. Further refinements of the premises of the model chosen are under consideration.

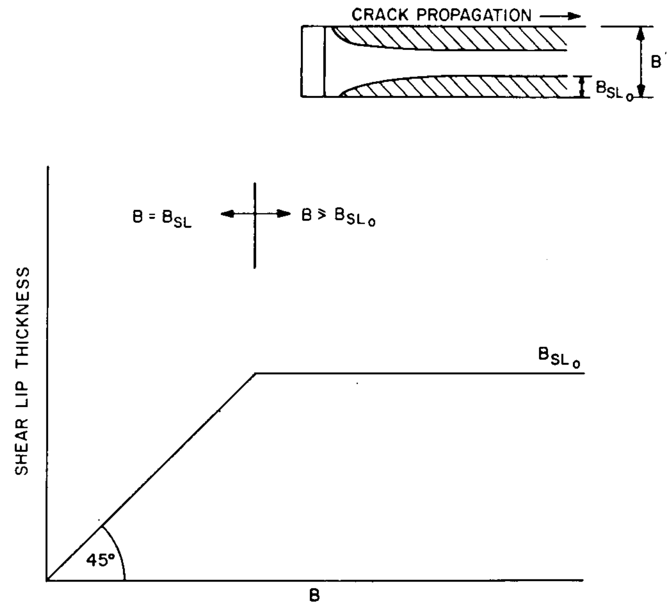


Fig. 6a—Postulated relationship between the sheet thickness and the amount of shear-lip thickness

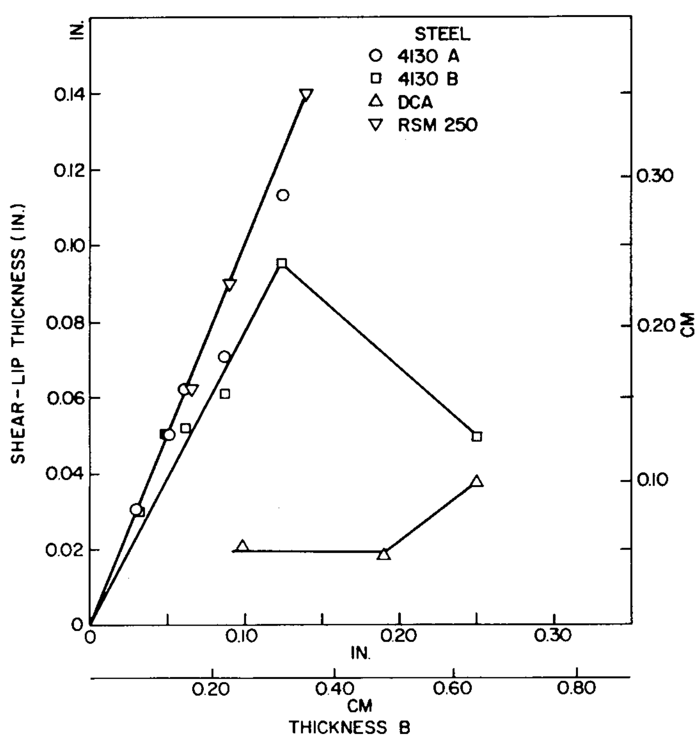


Fig. 6b—Measured shear-lip thickness vs specimen thickness B for four steels

CRITICAL CRACK LENGTH AT VARIOUS LEVELS OF OPERATING STRESS

Loads acting on a structural member cannot be precisely defined since fabricating stresses resulting from misalignment, welding, and rivet coupling can only be estimated. Further, the alloy strength will vary slightly from sheet to sheet, and even sheet thickness will fluctuate. Therefore, a reasonable estimate of K_c is a helpful design parameter.

In Fig. 7 the K_c dependence on thickness for the steels is compared; average values are seen to describe three of these steels over several ranges of thickness. Using these average values and various levels of operating-stress-to-yield-stress ratios σ_{op}/σ_{ys}, the crack lengths causing failure can be calculated and are shown in Fig. 8. Crack length is computed as

$$2a_c = \frac{2}{\pi}\left(\frac{K}{\sigma_{op}}\right)^2. \quad (6)$$

The practicality of inspection techniques to insure against the presence of cracks of critical lengths in any structure should be a factor in material selection.

SUMMARY

The influence of sheet thickness on the fracture-resistance parameter K_c for the steels investigated cannot be satisfactorily represented by the model proposed. It is suggested that factors other than geometry may be important considerations, such as chemistry, rolling practice, etc. Having established these preliminary relationships for shelf stock, it now becomes important to separate the effects of all variables by testing a thickness series for materials of identical chemistry, rolling practice, etc. Such discriminations may help clarify the inconsistencies noted in the application of the model selected and assist in the development of a more precise model.

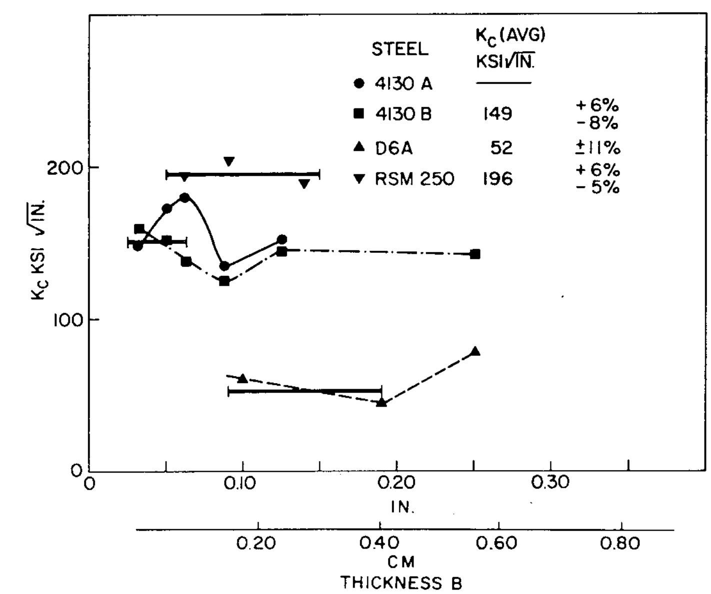


Fig. 7 – Fracture resistance K_c for four steels vs specimen thickness B. The heavy lines indicate average values.

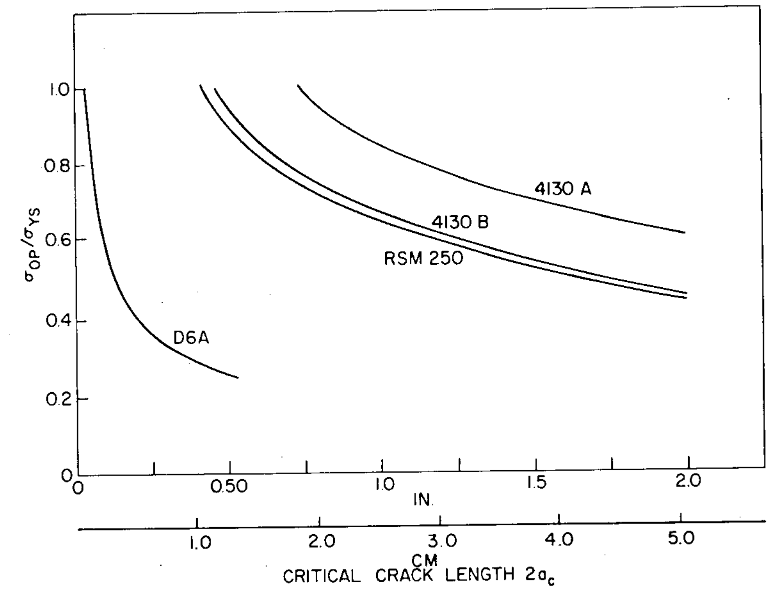


Fig. 8—Critical crack length $2a_c$ vs operating-stress-to-yield-stress ration σ_{op}/σ_{ys} for four steels

Instead of gradual degradation of the K_c value with increasing thickness, a trend toward constancy of value over a limited thickness range was observed. These values were used to estimate the crack length causing failure at various levels of operating-stress-to-yield-stress ratio σ_{op}/σ_{ys}. Such information should be helpful not only to the designer but to those responsible for periodic inspection of vulnerable structures.

REFERENCES

1. A.M. Sullivan and C.N. Freed, "The Influence of Geometric Variables on K_c Values for Two Thin Sheet Aluminum Alloys," NRL Report 7270, June 17, 1971.
2. C.N. Freed, A.M. Sullivan, and J. Stoop, "Comparison of Plane-Stress Fracture Toughness for Three Aluminum Sheet Alloys," NRL Report 7299, Aug. 11, 1971.
3. C.N. Freed, A.M. Sullivan, and J. Stoop, "Influence of Dimensions of Center-Cracked Tension Specimen on K_c," ASTM STP 514, 1972.
4. A.M. Sullivan, J. Stoop, and C.N. Freed, "The Influence of Sheet Thickness Upon the Fracture Resistance of Structural Aluminum Alloys," ASTM STP 536, 1973.
5. A.M. Sullivan and C.N. Freed, "Plane Stress Fracture Resistance of One Steel Sheet and Two Titanium Sheet Alloys," NRL Report 7332, Oct. 27, 1971.
6. C.N. Freed, A.M. Sullivan, and J. Stoop, "Crack-Growth Resistance Characteristics of High-Strength Sheet Alloys," NRL Report 7374, Jan. 31, 1972.
7. A.M. Sullivan, J. Stoop, and C.N. Freed, "Plane Stress Fracture Resistance of High-Strength Titanium Alloy Sheet," *Titanium: Science and Technology Proceedings*, Second International Conference on Titanium, Plenium Press, 1973.

8. C.N. Freed, A.M. Sullivan, and J. Stoop, "Effect of Sheet Thickness on the Fracture Resistance K_c Parameter for Titanium Alloys," NRL Report 7464, Nov. 8, 1972.

9. C.E. Fedderson, "Evaluation and Prediction of the Residual Strength of Center Cracked Tension Panels," in ASTM STP 486, 1971, p. 50.

10. D. Broek, "The Residual Strength of Aluminum Alloy Sheet Specimens Containing Fatigue Cracks or Saw Cuts," National Aerospace Laboratory (Amsterdam) Technical Report NLR-TR M.2143, Mar. 1966.

11. W.F. Brown, Jr., and J. E. Srawley, "Plane Strain Crack Toughness Testing of High-Strength Metallic Materials," ASTM STP 410, 1966.

12. J.I. Bluhm, "A Model for the Effect of Thickness on Fracture Toughness," Proc. ASTM **61,** 1324 (1961).

13. J. M. Krafft, A.M. Sullivan, and R.W. Boyle, "Effect of Dimensions on Fast Fracture Instability of Notched Sheet," in *Proceedings of Crack Propagation Symposium, Cranfield, U.K., 1961*, Cranfield College of Aeronautics, 1962.